

Microorganisms and Higher Plants for Waste Water Treatment¹

B. C. WOLVERTON, R. C. McDONALD, AND W. R. DUFFER²

ABSTRACT

Batch experiments were conducted to compare the waste water treatment efficiencies of plant-free microbial filters with filters supporting the growth of reeds (*Phragmites communis*), cattail (*Typha latifolia*), rush (*Juncus effusus*), and bamboo (*Bambusa multiplex*). The experimental systems consisted of two components in series. The first component was an anaerobic settling-digestion container. The second was a "nonaerated" trough filled with rocks, decreasing from large rocks (up to 7.5-cm diam) at the bottom, to pea gravel (0.25- to 1.3-cm diam) at the top. The plant-free microbial filter was equally effective in carbonaceous BOD, (5-d biochemical O₂ demand) removal. The vascular aquatic plant series enhanced ammonia removal, and consequently improved nitrogenous BOD, removal. Under the conditions of these experiments, raw sewage with initial BOD₅'s of 100 mg/L can be upgraded to meet secondary standards with 6 h in component 1, and 6 h in a plant-free filter or filter using cattail, rush, or reed. When initial BOD₅'s are approximately 450 mg/L, 24 h in component 1, 29 h in a reed filter are required to meet secondary standards. Total N removal studies were conducted, which demonstrated that a reed system is capable of removing NO₃-N and NH₄-N simultaneously, probably through a common NO₃-N intermediary, then to N₂. Overall, the reed system was superior to all others evaluated in this research project.

Additional Index Words: microbial filter, *Phragmites communis*, *Typha latifolia*, *Juncus effusus*, *Bambusa multiplex*, domestic waste water.

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Domestic waste water treatment is one of the major problems confronting every community and city in the United States. Presently, aerobic treatment processes are used almost exclusively in large and small cities in the United States. The activated sludge process is used for large cities; the trickling filter process and facultative lagoons are more popular for small cities.

The least expensive systems are lagoons, which depend on algae to supply O₂ photosynthetically. The other two major aerobic processes require much larger initial investments to design and construct, and have higher operational costs (personnel and energy). The projected costs associated with these systems, mainly due to the inflation of energy prices, have caused a surge in the development of alternative biological processes such as the one contained herein.

Anaerobic processes have low energy requirements, compared with aerobic processes, which need either mechanical aeration or liquid distribution systems. The anaerobic cycle depends on microorganisms that live in the absence of free O₂ and utilize chemically bound O₂. This process received little attention in waste water treatment during past years because of slow bacterial growth rates and sensitivity of the microorganisms to variables such as temperature, pH, shock loading, etc. Recent advancements have helped revive interest in anaerobic filter technology (Jewell et al., 1981; Koon et al., 1979; Switzenbaum and Jewell, 1978; Young and McCarty, 1969). The anaerobic filter method is an attached-growth process in which rock or an inert media is used to provide a stable surface area for microbial attachment and growth. Therefore, microorganisms are partially retained in the system as the waste water passes through. Mean cell residence times of approximately 100 d can be achieved with short hydraulic retention times (Metcalf & Eddy, Inc., 1979).

Interest in the anaerobic filter comes at a time of active research in the use of vascular aquatic plants for waste water treatment (Dinges, 1978; Duffer and

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Moyer, 1978; O'Brien, 1981; Stephenson et al., 1980; Tourbier and Pierson, 1976; Wolverton, 1979; Wolverton and McDonald, 1979). A hybrid system that consisted of a microbial attached-growth filter in which reeds (*Phragmites communis*) were rooted was studied by Wolverton (1982) and found to be a very effective system, superior to an anaerobic filter without the incorporation of higher plants. In this study, as well as those contained in this report, sealed chambers were used as anaerobic settling tanks to hold the freshly collected waste water for 24 h prior to transferring it to the filter. The settling tank is especially necessary for the design of a system serving a community, in order to prevent filter clogging.

This paper contains basic waste water data obtained during screening studies to evaluate and compare the effectiveness of cattail (*Typha latifolia*), rush (*Juncus effusus*), and bamboo (*Bambusa multiplex*) with that of reed in similar microbial filter-vascular plant waste water treatment systems. New reed experiments were conducted using waste water with high 5-d biochemical O₂ demand (BOD₅) (> 300 mg/L BOD₅), produced by mixing 1 part water hyacinth juice with 19 parts raw sewage in order to ascertain its maximum capacity. Water hyacinth juice was used to elevate the BOD₅, because it provides a natural concentrate of carbohydrates, proteins, and minerals.

Recognizing at the end of these series of batch experiments that a significant conversion of ammonia-N (NH₃-N) to a nonorganic form occurred as indicated by

a corresponding decrease in Kjeldahl N, further experiments with nitrate-spiked solutions were also performed to examine the total N picture.

MATERIALS AND METHODS

Experimental System Design

Six separate experimental systems such as the one shown in Fig. 1 were maintained in a greenhouse. Each system consisted of two components in series. The first component was a plastic, covered reservoir with 113-L capacity, which was used as the anaerobic settling tank. The second component was a galvanized steel trough filled to a depth of 16 cm with railroad rocks (2.5-7.5 cm in diam) and to a depth of 5 cm with pea gravel (0.25-1.3 cm in diam). The trough containing reed, and a second trough free of plants, measured 50.5 cm wide by 30.5 cm deep by 298 cm long. The other 4 troughs were 50.5 cm wide by 30.5 cm deep by 183 cm long. Of these troughs, one each was planted with cattail, rush, and bamboo. The fourth trough was kept free of higher plants. Each trough was fitted with a bottom valve on the end opposite where the anaerobically settled waste water was added, to collect samples and drain the tanks.

Experimental Procedures

In January and February 1981, two anaerobic systems were used to perform the following study. The trough in the first system was plant-free; the second trough contained reed. For each system, 82.6 L of raw sewage was mixed with 4.4 L of fresh water hyacinth juice in order to significantly elevate the BOD₅. The water hyacinth juice was obtained by processing fresh water hyacinth through a portable, electric screw press built from a design provided by Dr. Larry Bagnall, University of Florida. Aliquots were removed from the settling tank initially and after 24 h. The settled and partially digested waste water was pumped into the troughs, and aliquots were removed at 6-, 24-, and 48-h inter-

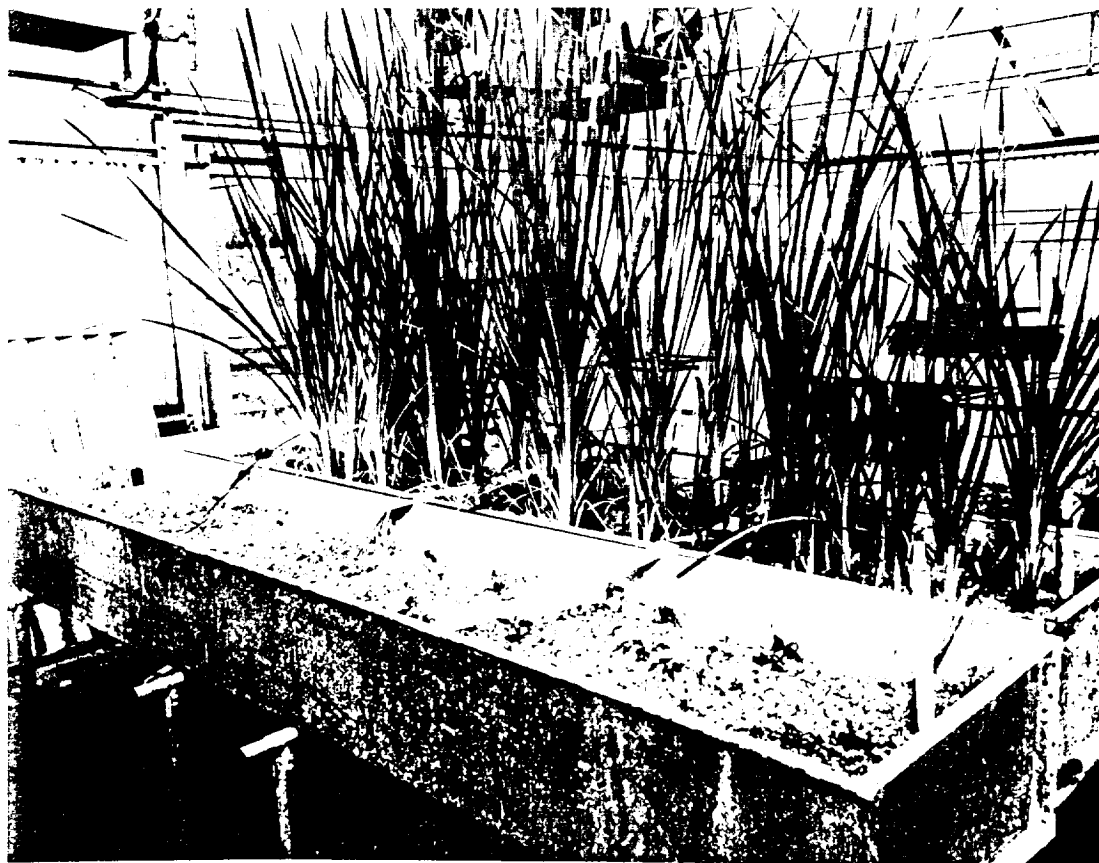


Fig. 1—A plant-free microbial filter and a combination system using *Typha latifolia*.

Table 1—Mean, standard deviation (σ), and upper limit (U) concentrations ($P = 0.95$) of the BOD₅, TSS, and TDS after settling for 24 h, followed by microbial filter treatment with and without plants.

		Concentration														
		Settling tank						Microbial filter								
Param- eter	Microbial filter	Initial		6 h		24 h		6 h			24 h			48 h		
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	U	Mean	σ	U	Mean	σ	U
mg/L																
BOD, [†]	Plant-free	114.5	27.3	66.2	25.0	61.6	23.9	17.4	11.2	37.3	8.2	4.8	16.7	6.2	4.4	14.0
	Bamboo	114.5	27.3	66.2	25.0	65.8	23.0	31.4	18.6	64.6	21.4	13.0	44.5	13.0	12.5	35.2
	Rush	114.5	27.3	66.2	25.0	67.2	23.1	17.8	12.2	39.4	7.4	5.5	17.2	3.1	2.2	7.1
	Reed	109.9	34.2			71.7	22.8	8.9	6.3	20.5	2.8	2.4	7.1			
	Cattail	116.8	27.2	94.2	32.4	80.1	32.6	17.4	14.7	44.8	10.4	8.3	25.7	5.2	3.4	11.6
TSS [‡]	Plant-free	54.4	18.7	30.9	12.2	25.0	6.9	12.7	4.0	19.8	10.9	7.5	24.3	3.9	9.7	
	Bamboo	54.4	18.7	30.9	12.2	23.0	8.8	17.1	12.2	38.9	7.0	4.9	15.7	8.4	10.6	27.3
	Rush	54.4	18.7	30.9	12.2	24.8	10.7	17.5	7.2	30.3	13.9	5.8	24.3	4.4	5.9	14.9
	Reed	68.4	34.6			36.0	20.4				5.9	4.6	14.4			
	Cattail	64.4	37.6	34.4	11.9	29.0	8.1	11.6	7.0	24.7	15.3	17.9	48.6	8.6	9.8	26.8
TDS [¶]	Plant-free	376	79	360	96	361	73	374	73	503	391	83	539	405	88	561
	Rush	376	79	360	96	376	83	452	106	641	467	133	704	466	149	731
	Reed	376	79	360	96	387	96	455	60	563	487	72	616	528	101	709
	Cattail	371	48	327	62	337	28	398	32	468	416	66	539	419	71	551

† BOD₅ = 5-d biochemical O₂ demand.

‡ Data published by Wolverton, 1982.

§ TSS = Total suspended solids.

¶ TDS = Total dissolved solids.

Table 2—Mean, standard deviation (σ), and upper limit (U) concentrations ($P = 0.95$) of the TKN, NH₃-N, and TP after settling for 24 h, followed by microbial filter treatments with and without plants.

		Concentration												
		Settling tank						Microbial filter						
Parameter	Microbial filter	Initial		24 h		6 h			24 h			48 h		
		Mean	σ	Mean	σ	Mean	σ	U	Mean	σ	U	Mean	σ	U
mg/L														
TKN†	Plant-free	17.0	8.4	16.0	8.2	14.7	7.1	27.4	12.3	4.7	20.7	12.5	3.8	19.3
	Bamboo	17.0	8.4	15.9	6.7	12.1	5.9	22.6	8.9	2.6	13.5	9.3	4.6	17.5
	Rush	17.0	8.4	15.7	7.0	7.8	2.1	11.5	5.9	1.7	8.9	5.7	3.0	11.1
	Reed‡	16.1	5.3						2.9	1.8	6.2			
	Cattail	11.8	6.5	13.2	6.4				4.7	2.4	9.2	6.1	2.2	10.3
NH ₃ -N	Plant-free	9.2	5.8	10.9	5.5	9.8	2.7	14.6	8.5	3.2	14.2	8.8	2.5	13.3
	Bamboo	9.2	5.8	11.4	5.1	5.8	2.7	10.6	2.7	2.4	7.0	2.5	2.6	7.1
	Rush	9.2	5.8	11.1	6.5	1.2	0.9	2.8	0.8	1.0	2.6	0.1	0.1	0.3
	Reed‡	12.4	4.8						0.6	0.5	1.5			
	Cattail	10.9	5.6	11.6	6.2				0.6	0.5	1.2	0.4	0.4	1.2
TP§	Plant-free	6.2	1.5	5.7	1.5	5.9	1.4	8.3	5.5	1.3	7.8	7.5	3.0	12.9
	Bamboo	6.2	1.5	6.2	1.3	5.8	2.1	9.6	5.7	2.3	9.8	7.1	1.9	10.6
	Rush	6.2	1.5	6.0	1.5	4.9	1.9	8.3	4.2	2.2	8.1	6.0	1.8	9.1
	Reed‡	4.4	1.2						2.0	0.6	3.1			
	Cattail	5.3	3.4	5.9	3.3				3.0	1.9	6.6	3.4	1.8	6.8

† TKN = Total Kjeldahl N.

‡ Data published by Wolverton, 1982.

§ Total P.

vals. Atmospheric greenhouse temperatures were recorded daily. The 5-d biochemical O₂ demand (BOD₅), total Kjeldahl N (TKN), and ammonia-N (NH₃-N) were determined on each sample (APHA, 1976).

Nine procedures, outlined below, were conducted with a cattail and a plant-free system, which had been conditioned with sewage for > 2 months during March and April 1981. During this period, troughs with rush and bamboo were established and conditioned in the same manner. Starting in late May 1981, 13 of the same procedures were performed with the new systems and a plant-free system. The cattail experiments did not continue during the summer, because the greenhouse was too hot to sustain them in a healthy condition. The rush and bamboo did not seem to be affected by the heat during midday.

For each of these procedures, 72 L of raw sewage was pumped from the influent manhole at the National Space Technology Laboratories' Sewage Lagoon no. 1 directly into each settling tank, and transported back to the greenhouse. An initial sample was taken, plus another one after 6 h of settling from only one of the settling tanks. At the end of

24 h, aliquots were taken from each of the settling tanks prior to pumping the contents into each respective trough. Further samples were taken via valves at the bottom of the troughs at 6-, 24-, and 48-h intervals.

Each of the samples, except the 6-h settling samples, were analyzed for pH, BOD₅, total suspended solids (TSS), total dissolved solids (TDS), TKN, NH₃-N, and total P (TP) (APHA, 1976). The only analyses performed on the 6 h settling sample were BOD₅ and TSS. Atmospheric greenhouse temperatures were taken daily. The filter effluent temperatures were taken at the time of sample collection.

In December 1981, six procedures using tap water spiked with KNO₃ were performed in a manner similar to the previous experiments, except the solution was not held for 24 h prior to introducing it into the troughs. The plant-free, bamboo, and reed troughs were the only ones used. The cattail system was eliminated in the summer and not re-established. The rush trough was in the process of being repaired at this time, and NH₃-N, TKN, NO₃-N were performed on all

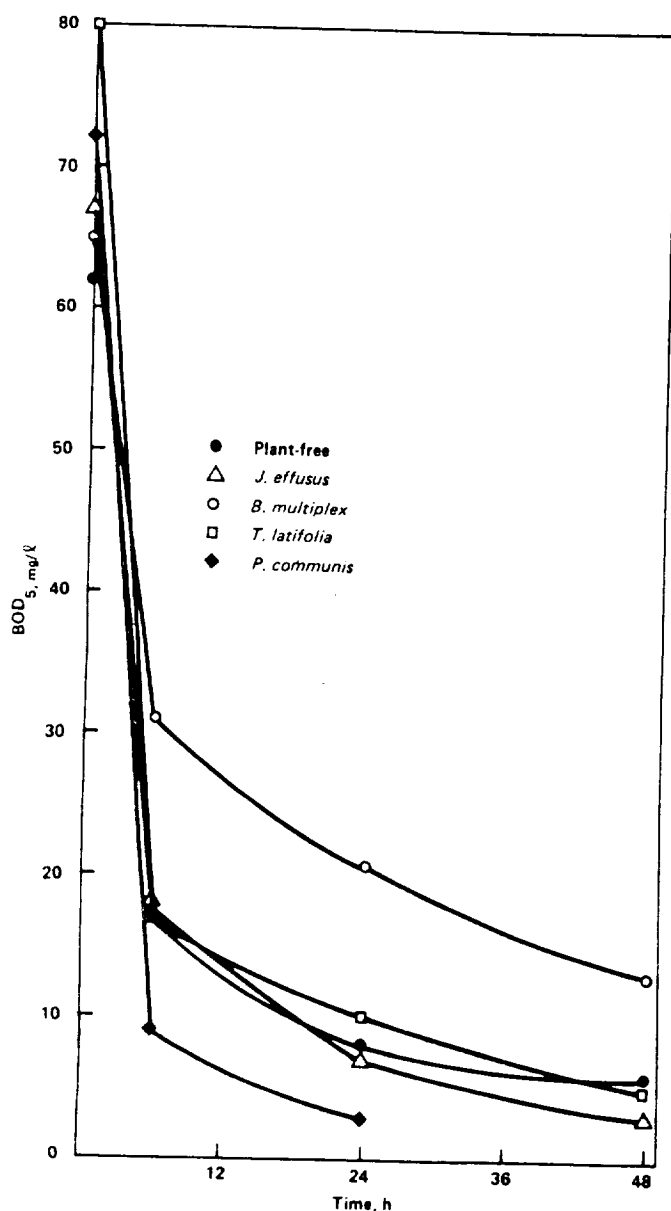


Fig. 2—BOD₅ vs. exposure time in the microbial filter.

samples; TP, pH, and temperature measurements were made on initial and final samples.

In March, six sewage experiments were performed again in a manner similar to the first experiments. The cattail system was added and the monitoring consisted of the analyses outlined for the tap water. The initial sample was removed after the waste water, which had been in the settling tank 24 h, was spiked with ammonium nitrate (NH₄NO₃). Once it was established that the NH₄-N was not converted to NO₃-N, 10 procedures using sewage, spiked with ammonium nitrate, were performed with the same monitoring schedule.

RESULTS AND DISCUSSION

Table 1 contains the mean, standard deviation (σ), and upper limit (U) concentrations of BOD₅, TSS, and TDS data obtained from the series of batch experiments conducted with each species. The upper limit concentrations are the maximum concentrations at the 95% confidence level ($P = 0.95$) computed by the equation:

$$U = \text{mean} + t_{0.95(n-1)}(\sigma)$$

Table 3—Mean atmospheric and filter effluent temperatures measured during each respective experimental period for which data appears in Table 1 and 2.

Experiment	Mean temperature		
	Atmospheric		Filter effluent
	Minimum	Maximum	
	°C		
Bamboo	23.0	37.5	26.1
Cattail	16.0	34.3	25.0
Reed	17.0	40.0	23.0

where σ is the standard deviation, and $t_{0.95(n-1)}$ is a numerical quantity for $n - 1$ degrees of freedom (Ostle, 1972). Data by Wolverton (1982) on a reed-microbial filter evaluated under similar conditions is included for comparative purposes.

According to the data presented in Table 1 and Fig. 2, a plant-free microbial filter is as efficient in carbonaceous BOD₅ removal as one supporting the growth of rush or cattail. The terrestrial species, bamboo, performed the poorest in BOD₅ removal in comparison with the other systems. Although the mean BOD₅ values for all filters except the bamboo were under the 30 mg/L EPA requirement for secondary treatment after 6 h of treatment, only the reed system's performance was consistent enough to compute an upper limit value of 20.5 mg/L, well under 30 mg/L, at the 95% confidence level. However, after 24 h of exposure, the performances of all filters, except the bamboo, were efficient enough to bring the mean and the U value ($P = 0.95$) well below a 30 mg/L discharge requirement for BOD₅.

At this point, it must be pointed out that a significant portion of the BOD₅ reduction in the settling tank was a result of biodegradable solids settling out, and only the soluble BOD₅ substances passing into the filters. The settled solids also contain O₂-demanding substances, which require further detention in order for them to undergo complete anaerobic digestion and stabilization. If the liquid portion of the waste solution is left in contact with the settled solids, simpler, soluble substances can be released, which exert a BOD₅. The overall result is an initial drop in BOD₅, followed by a slight increase. This effect can be seen from the settling data in Table 1.

Unfortunately, the waste water collected at the National Space Technology Laboratories was low in TSS, as compared with municipal waste water. However, the settling tank was still incorporated into the experimental procedure, because it is definitely a necessary feature for large systems with high suspended solids in order to prevent filter clogging. Consequently, the TSS concentrations leaving the settling tanks after 24 h were under 30 mg/L (except for the previous reed study). After 24 h in the microbial filters, the statistical upper limits ($P = 0.95$) were all well under 30 mg/L, except for the cattail filter. The reed filter from a previous study was once again the superior system in TSS removal.

The dissolved solids tended to increase in all the systems over the 48-h exposure periods. The TDS increased by 12.2% in the plant-free system over the 48-h trough exposure period, 23.9% in the bamboo system, 36.4% in the rush system, and 24.3% in the cattail system. This was probably due to a concentration effect

Table 4—Mean reed system data for experiments conducted in January–February 1981, using waste water spiked with water hyacinth juice.

		Concentration									
		Settling tank				Microbial filter					
Parameter	Microbial filter	Initial		24 h		6 h		24 h		48 h	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
mg/L											
BOD ₅ †	Plant-free	472	122	306	135	172	9	67	37	38	16
	Reed	461	134	318	130	97	52	36	21	21	17
TKN‡	Plant-free	27.9	1.3	23.8	2.5	16.3	2.0	13.3	1.6	12.0	1.6
	Reed	28.3	1.3	26.2	2.7	7.8	0.9	4.3	2.0	4.5	0.9
NH ₃ -N	Plant-free	13.0	3.9	11.1	3.5	9.7	1.7	7.7	1.4	7.3	0.5
	Reed	14.1	2.6	13.6	3.6	1.9	1.6	0.6	0.6	0.3	0.5

† BOD₅ = 5-d biochemical O₂ demand.

‡ TKN = Total Kjeldahl N.

Table 5—Mean N data for experimental systems treating tap water spiked with KNO₃.

Microbial filter	Param-eter	Mean concentration							
		Initial		6 h		24 h		48 h	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ
mg/L									
Plant-free	NO ₃ -N	12.3	1.2	5.3	2.0	1.6	1.2	0.25	0.25
Bamboo		11.8	1.2	2.6	1.0	0.05	0.02	0.05	0.02
Reed		12.3	0.9	3.3	0.64	0.39	0.39	0.05	0.05
Plant-free	NH ₃ -N	0.2	0.1	2.1	1.3	1.9	0.9	2.2	0.8
Bamboo		0.2	0.2	0.3	0.6	0.5	0.6	0.2	0.1
Reed		0.2	0.2	0.1	0.2	0.1	0.1	0.2	0.2
Plant-free	TKN†	2.6	0.7	4.3	0.6	4.3	0.6	5.0	1.1
Bamboo		2.5	0.6	4.0	1.3	3.3	1.0	3.6	0.9
Reed		2.5	0.7	2.8	0.8	3.5	2.0	3.1	1.0

† TKN = Total Kjeldahl N.

Table 6—Mean N data for the experimental systems treating plain waste water just prior to those studies with NH₄NO₃-spiked waste water.

Microbial filter	Param-eter	Mean concentration							
		Initial†		6 h		24 h		48 h	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ
		mg/L							
Plant-free	NO ₃ -N	0.08	0.03	0.14	0.006	0.17	0.09	0.15	0.03
Cattail		0.11	0.03	0.19	0.09	0.19	0.09	0.22	0.12
Rush		0.09	0.04	0.15	0.10	0.13	0.08	0.10	0.03
Reed		0.13	0.10	0.22	0.10	0.49	0.25	0.42	0.03
Plant-free	NH ₃ -N	15.0	3.0	12.3	0.9	12.0	1.2	11.6	1.0
Cattail		15.7	4.2	6.5	1.3	4.6	1.3	3.0	1.0
Rush		16.7	4.1	5.7	1.0	3.4	1.2	2.4	1.1
Reed		15.1	3.1	1.9	0.4	0.6	0.4	0.7	0.6
Plant-free	TKN‡	20.0	3.6	16.3	2.0	15.1	1.9	15.4	1.0
Cattail		21.0	4.0	10.3	1.2	7.8	0.5	5.4	1.1
Rush		21.4	3.3	10.3	1.2	7.0	0.4	5.8	1.1
Reed		18.4	3.3	6.5	0.3	5.0	0.8	5.2	1.7

† Initial sample was taken from the settling tanks in which waste water was allowed to anaerobically settle and digest for 24 h, and then spiked with NH₄NO₃ just prior to introducing them into the filters.

‡ TKN = Total Kjeldahl N.

from the loss of liquid through evaporation or evapotranspiration. However, volume reductions in these experiments were not measured. The volume loss was monitored in the earlier reed experiments conducted by Wolverton (1982). In these experiments, the reed and plant-free systems lost an average of 21.8 and 12.3%, respectively, of their original volume over a 48-h period.

The total P data presented in Table 2 indicates little reduction in this nutrient by any of the systems except the cattail. In fact, the total P concentration slightly increased over the experimental period for the plant-free and bamboo systems. A combination of evaporation and evapotranspiration, and lack of significant plant absorption created this effect.

The most striking difference in the plant-free system and those containing plants is in Kjeldahl and NH₃-N reduction rates after 24 h (Table 2). The rush and cattail filters reduced the NH₃-N by 93 and 95%, respectively, after 24 h. In fact, 89% of the NH₃-N in the rush filter was gone in just 6 h. The bamboo filter was more efficient than the plant-free system, but less so than the other two. It reduced the NH₃-N by 49 and 76% after 6 and 24 h, respectively. The Kjeldahl N, a measure of the total organic and NH₃-N concentration, was reduced by all systems in a pattern similar to that of NH₃-N. Statistically, the rush, reed, and cattail filters were superior in both TKN and NH₃-N removal to the plant-free filter.

The greenhouse and filter effluent temperatures for this series of experiments are presented in Table 3.

The initial mean waste water pH varied from 6.9 to 7.2. The mean, 48-h pH of the effluent from the plant-free filter was 7.3, the bamboo and rush filters were 7.0, and the cattail filter was 6.6.

Based on the superior results of the first reed study by Wolverton (1976), further experiments were conducted with reed to determine its response to waste solutions much higher in unstabilized contaminants. Therefore, raw sewage was mixed with water hyacinth juice to produce a solution significantly higher in BOD₅ than that used in the first experiments. The BOD₅ and N analyses of these experiments are presented in Table 4.

With the high BOD₅ waste solution, the BOD₅ of the waste water was reduced by 33% during the initial 24-h process in the settling tank. The average BOD₅ and TKN leaving the settling tanks were 312 and 24.0 mg/L, respectively. On a mass basis, the TKN requires 4.57 times its mass in O₂ for complete oxidation. Therefore, of the remaining BOD₅, approximately two-thirds is carbonaceous BOD₅ with the remaining nitrogenous. In the reed filter, the BOD₅ reduction of both forms is a single-step process as demonstrated by the rapid reduction in BOD₅, TKN, and NH₃-N in just 6 h. The plant-free system's BOD₅ remained approximately two times higher than the reed system over the same exposure time; the BOD₅ vs. exposure time is presented in Fig. 3.

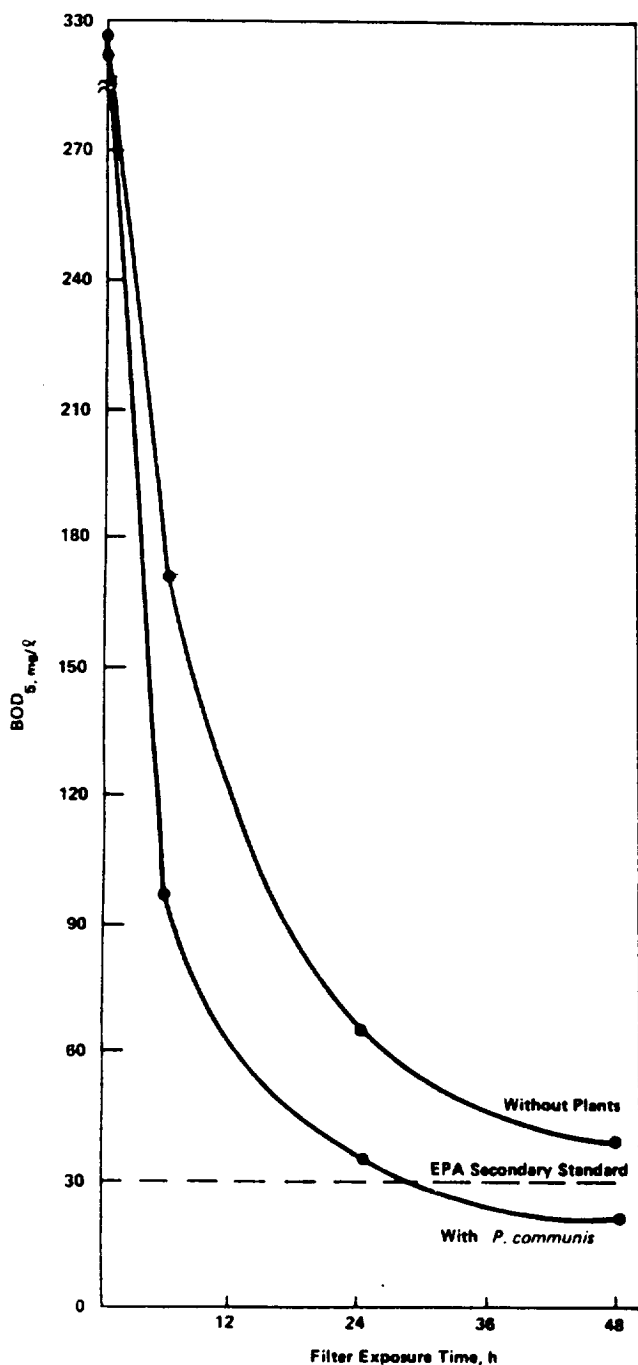


Fig. 3—BOD₅ vs. exposure time for the *P. communis* experiments with high BOD₅ waste.

In order to meet secondary BOD₅ standards of 30 mg/L, a minimum exposure time of 29 h in the combination filter would be needed if the BOD₅ entering the filter were approximately 300 mg/L.

The last three sets of data generated using tap water spiked with NH_4NO_3 , plain waste water, and waste water spiked with NH_4NO_3 , were performed in order to get a clearer picture of the N conversion processes in the filters. The data presented in Table 5 for those experiments conducted with NH_4NO_3 -spiked tap water indicates that the plant-free filter used in these studies did effect denitrification as demonstrated by the $\text{NO}_3\text{-N}$ loss, without significant corresponding increases in the

Table 7—Mean N data for experimental systems treating waste water spiked with NH_4NO_3 .

Microbial filter	Parameter	Mean concentration							
		Initial†		6 h		24 h		48 h	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ
mg/L									
Plant-free	NO ₃ -N	14.6	1.6	0.43	0.47	0.11	0.02	0.28	0.23
Bamboo		14.5	1.8	0.12	0.03	0.15	0.06	0.17	0.06
Rush		13.9	1.8	3.7	2.4	0.72	0.88	0.50	0.77
Reed		14.5	1.8	1.6	1.3	0.16	0.08	0.22	0.14
Plant-free	NH ₄ -N	33.3	6.4	22.7	3.9	20.8	0.8	19.8	3.0
Bamboo		33.0	5.6	16.5	3.5	14.5	3.0	12.2	2.6
Rush		33.6	7.4	16.7	3.0	14.6	2.3	14.2	3.3
Reed		32.6	6.7	5.9	2.2	0.5	0.7	0.2	0.1
Plant-free	TKN‡	51.1	3.5	25.6	0.7	23.8	2.1	23.7	2.4
Bamboo		50.3	9.8	21.2	3.2	16.8	3.6	15.0	3.7
Rush		52.4	5.7	20.7	2.8	16.9	2.2	17.2	3.2
Reed		42.3	8.7	11.6	5.8	4.4	1.1	4.0	1.0

† Initial sample was taken from the settling tanks in which waste water was allowed to anaerobically settle and digest for 24 h, and then spiked with NH_4NO_3 , just prior to introducing them into the filters.

‡ TKN = Total Kjeldahl N.

$\text{NH}_4\text{-N}$ or TKN. The addition of either bamboo or reed into the system increased the rate of denitrification over that in a plant-free filter.

The data presented in Table 6 for $\text{NH}_4\text{-N}$ and TKN was very similar to that already presented in Table 2. One exception was that the data for the rush filter indicates that perhaps this filter's capacity for $\text{NH}_4\text{-N}$ removal was exceeded. In Table 2, the rush filter was capable of reducing $\text{NH}_4\text{-N}$ from 11.1 mg/L to 1.2 mg/L in 6 h; in Table 6, the rush filter reduced the $\text{NH}_4\text{-N}$ from 16.7 mg/L to only 5.7 mg/L in 6 h. No significant increase in $\text{NO}_3\text{-N}$ occurred as indicated by the data in Table 6. Therefore, the $\text{NH}_4\text{-N}$ in the filters containing plants must have been absorbed by the plants or converted to a N form, which was then converted to N_2 and lost from solution to the atmosphere. Considering that the plants' coverage of the filters was at a maximum, and they were not cut back during this study period, plant absorption of the $\text{NH}_4\text{-N}$ was probably insignificant compared with the latter explanation for the loss of $\text{NH}_4\text{-N}$ without an increase in TKN or $\text{NO}_3\text{-N}$.

The data presented in Table 7 is especially interesting. The plant-free filter performed in a normal anaerobic mode, performing "anoxic" denitrification, a process by which $\text{NO}_3\text{-N}$ is converted to N_2 without O_2 , without efficiently converting $\text{NH}_4\text{-N}$ or TKN to nonorganic forms. The bamboo and rush filters performed similar to the plant-free filter, with only a slight improvement in $\text{NH}_4\text{-N}$ reduction. The $\text{NH}_4\text{-N}$ removal capacities of these filters exposed to initial $\text{NH}_4\text{-N}$ concentrations of approximately 33 mg/L had been exceeded. The bamboo and rush filters can handle $\text{NH}_4\text{-N}$ levels of approximately 11 mg/L as demonstrated in Table 2.

However, the reed filter demonstrated efficiency in the removal of both oxidized and reduced N forms. From the data presented in Table 7, the TKN, a measure of the organic-N and $\text{NH}_4\text{-N}$ (the reduced N form), in the reed filter was reduced by 90.5% from 42.3 to 4.0 mg/L in 48 h. The $\text{NO}_3\text{-N}$ (the major oxidized N form present) was reduced at the same time by 98.5% from 14.5 to 0.22 mg/L in 48 h. Therefore, the overall TN (TKN + $\text{NO}_3\text{-N}$) was reduced by 92.6% from 56.8 to

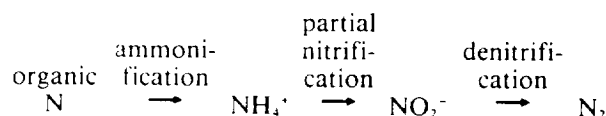
Table 8—Mean, TP, pH, and effluent and atmospheric temperatures for the studies focusing on N removal in Table 5-7.

Microbial filter	System	TP†				pH				Effluent temp.				Atm. temp.			
		I‡		48 h		I		48 h		I		48 h		Min		Max	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
		mg/L												C			
Plant-free	Tap water with KNO ₃	3.2	2.6	3.7	2.7	8.1	0.3	7.4	0.1	17.7	1.8	16.4	1.8	11.0	3.0	33.1	6.1
	Waste water	3.4	1.1	5.0	1.0	7.1	0.3	7.4	0.3	20.6	1.1	19.5	3.7	12.7	2.5	36.5	6.5
	Waste water with NH ₄ NO ₃	4.5	2.4	2.4	1.2	7.1	0.1	7.7	0.2	22.6	1.1	21.6	2.7	17.1	4.2	36.9	4.3
Bamboo	Tap water with KNO ₃	3.3	2.6	3.4	2.4	8.3	0.2	7.0	0.2	17.9	2.1	16.4	1.8	11.0	3.0	33.1	6.1
	Waste water	3.7	1.2	2.1	0.4	7.0	0.2	7.0	0.1	20.3	1.0	19.8	3.7	12.7	2.5	36.5	6.5
	Waste water with NH ₄ NO ₃	5.7	1.6	1.6	1.2	7.2	0.2	7.1	0.1	22.5	1.1	21.6	2.6	17.1	4.2	36.9	4.3
Rush	Waste water	3.9	0.9	1.5	1.2	7.1	0.4	7.0	0.1	20.4	1.3	19.0	3.2	12.7	2.5	36.5	6.5
	Waste water with NH ₄ NO ₃	4.4	2.6	1.7	2.2	7.1	0.1	7.3	0.1	22.7	0.9	21.6	2.7	17.1	4.2	36.9	4.3
Reed	Tap water with KNO ₃	3.6	2.9	2.9	2.7	8.4	0.2	7.1	0.2	17.7	2.0	16.4	1.8	11.0	3.0	33.1	6.1
	Waste water	3.6	0.9	2.3	1.3	7.1	0.4	7.0	0.1	20.6	1.1	19.1	3.3	12.7	2.5	36.5	6.5
	Waste water with NH ₄ NO ₃	5.0	2.0	1.5	2.1	7.1	0.1	6.9	0.1	22.1	0.9	21.6	2.6	17.1	4.2	36.9	4.3

† TP = Total P.

‡ I = Initial reading.

4.22 mg/L. Since both NH₄-N and NO₃-N are rapidly lost in the reed filter, it suggests that the plant roots are contributing sufficient O₂ to the liquid to enhance nitrification, but not enough to sustain this zone in a complete aerobic state. Therefore, anoxic conditions conducive to denitrification prevail. Since nitrite is an intermediate in both the nitrification and denitrification processes, the most probable N pathway is:



The mean TP, pH, and effluent temperatures for these last three sets of data are compiled in Table 8 for background information.

CONCLUSIONS

In conclusion, a plant-free microbial filter is more effective in carbonaceous BOD₅ removal than in nitrogenous BOD₅ removal. When vascular aquatic plants are added to the filter, NH₄-N removal is enhanced, and nitrogenous BOD₅ removal is improved.

A reed-microbial filter system is not only efficient in NH₄-N removal, but also in NO₃-N removal. The data suggests that both forms are being converted to the common, intermediary NO₂-N, and then to gaseous N₂ evolved from the system. Consequently, the reed-microbial filter is the superior system studied to date.

The data suggests that raw sewage with initial BOD₅'s of approximately 100 mg/L can be treated to meet secondary standards following 6 h in an anaerobic settling tank and 6 h in plant-free, reed, rush, or cattail filters under the conditions of these experiments. The reed filter is statistically more reliable at the 6 h detention time.

When reed-microbial filters are used to treat waste water with initial BOD₅'s of approximately 450 mg/L, 24 h in the settling tank, and 29 h in the filter are required to meet the 30 mg/L standard for secondary treatment.

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